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AN INTRODUCTION TO CRACK PROPAGATION IN HIGH STRENGTH SHEET MATERIALS

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Prepared by W. E. Witzell
W. E. Witzell

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ABSTRACT: A discussion is presented of fracture mechanics and of the theory and test methods underlying tests which have been developed to evaluate the fracture toughness of sheet alloys.

Procedures have been devised at Astronautics for conducting fracture toughness tests at cryogenic temperatures and quantitative data have been developed for cold rolled Type 301 stainless steel sheet. The fracture toughness of this alloy at low temperatures decreases with increasing room temperature strength (achieved by cold working) above approximately 160,000 170,000 psi yield strength. Also, the fracture toughness in the transverse direction is significantly less than that in the longitudinal direction at sub-zero temperatures and may be a limiting design factor for this material when used at cryogenic temperatures.

Fracture toughness testing is being extended to cover temperatures down to -423°F and is being applied to measure the toughness of fusion butt welded joints in various high strength sheet alloys.

Prepared by W E Witzell
W. E. Witzell

Approved by A Hurlich
A. Hurlich
Research Group Engineer
Materials Research Group

AH:WEW:jn
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TO: Distribution

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INTRODUCTION:

The phenomenon of brittle fracture or fracture mechanics is a most interesting and too often neglected topic. As far back as 1920, Griffith (1) advanced his famous theories, followed by Westergaard(2) who was interested in crack propagation in concrete roads. The alarming catastrophic failures of all-welded ships during World War II led the Navy to back the research of G. R. Irwin (3). However, the average structural and design engineer was not interested in the problem since he was adequately armed (he thought) with data on ultimate and yield strengths, percent elongation, and modulus of elasticity, to say nothing of Poisson's ratio, generally obtained in tests at room temperature. The more advanced engineers have been exposed to the concept (if not the theory) of stress concentration factors so ably explained by Heins Neuber(4). The advent of high strength pressure vessels for rocket motor cases has steered the problem of brittle fracture to our very drawing boards. Further, the severe cryogenic environments of the liquid fueled missile combined with the previous problem and with the drive towards minimum weight structures has made the solution of the catastrophic fracture problem of utmost importance.

The Concept:

Basically, the theory states that if a material contains a crack, flaw, or other sharp discontinuity, there is a particular stress level at which the crack will propagate rapidly to failure. In a brittle material, this stress level is below the yield strength of the material. Equally important is the fact that a semi-ductile material may become extremely brittle at cryogenic temperatures or when subjected to multi-axial or rapidly applied loads. The Griffith-Irwin theory suggests that if the energy released by cracking exceeds the energy required to extend the cracks, the crack becomes self-propagating at a rapid rate until total failure results. The crack length at the onset of rapid propagation is known as the critical crack length.

It follows that a crack shorter than the critical crack length can and often does exist in metal components. In fact, this crack can propagate at a slow rate with an increase of stress and will stop growing if the load (stress) is reduced or held constant. This slow propagation will continue with an increase in stress until it reaches the critical crack length for the particular stress to which it is subjected, and then rapid fracture occurs.

Therefore, since failure is dependant on both crack length and stress, it is logical to seek a parameter that incorporates the two. If one were to know the stress level beyond which defects of a specified size are subject to catastrophically rapid propagation, it would be possible to establish a conservative design in which stresses would not exceed the safe level such that pre-existing flaws and defects would not propagate. The most generally used parameters that are indicators of the ability of a material to resist fracture are called fracture toughness (K_c) and crack extension force or strain energy release rate (G_c).

For an infinitely wide plate:

$$K_c = \sigma_G \sqrt{\pi a}$$

where K_c = fracture toughness ($Ksi\sqrt{in}$)
σ_G = gross section stress away from the cracked section at the maximum load (Ksi)
a = one half of the crack length at onset of rapid propagation (in.)

and

and $$G_c = \frac{(K_c)^2}{E}$$

where G_c = crack extension force (in#/in^2)

E = Young's Modulus of Elasticity

In general, the higher the K_c or G_c, the better are the toughness properties of the material and, therefore, the better the resistance to brittle fracture.

According to Campbell and Achbach[5], high strength steels that have G_c values of less than 600 are subject to brittle fracture.

Determination of G_c

Since the use of the fracture toughness concept is still in its infancy, standardization of testing for determination of K_c and G_c is practically non-existant, although both ASTM and ARTC committees are studying the problem.

The majority of tests(5) have been in three areas: (1) Edge notch specimens, (2) Charpy Impact Specimens, and (3) Center Notch Specimens.

The edge notch specimen has been used primarily for determination of stress concentration factors and more important, for the notch-unnotch ratio screening tests. The impact tests are designed to measure the total energy required for fracture. Neither of these two tests can provide fully adequate and quantitative design data.

The majority of the emphasis (in recent years) has been directed to the center-notch specimen. Irwin has directed his efforts toward developing tests that will duplicate the action of the material under service conditions and still allow a vigorous mathematical stress analysis. Since the catastrophic failure problem is so vital, a flurry of techniques and specimens have been developed.(5)

Generally, the specimen shape is rectangular, is pulled in tension, and contains a center slot perpendicular to the direction of loading. Although there are various ideas concerning the dimensions, rate of loading, etc., the largest area of difference of opinion concerns the slot itself. Most experimenters agree on a slot length that is 30 to 40% of the total width of the specimen. However, a large number feel that the radius of the tip of the crack should be small and resemble a "natural crack" or micro crack.

Christensen of Douglas(6) insists that a fatigue crack is the most "natural crack" that can be induced. Other notching methods include jeweler's saw cuts, Elox or Elektro-Jet (electrical discharge) cuts, and hydrogen embrittlement cracks.

Most researchers agree that any notch is sufficient that is sharp enough to induce some slow crack propagation prior to rapid crack growth leading to failure.

It is the opinion of the author that no crack should be induced by a method that will change the temper, or the physical or mechanical properties of the material in front of the crack.

It should be noted that a relatively blunt notch that may be acceptable for testing a ductile material, may not be and generally is not acceptable for testing a brittle material or a material that becomes brittle at cryogenic temperatures.

The two variables that must be measured to obtain G_c are maximum load and total crack length. The load is normally measured by the sensing devise on the testing machine. The two most prominent methods of estimating crack length are by observation of the fracture appearance (not completely reliable) after failure, and by a staining technique. In the latter, a drop of ink or dye (Zyglo works quite well) is placed in the tip of the crack. As the crack propagates slowly, the stain follows; but when the fast propagation begins, the dye cannot follow and the critical crack length is easily measured. This technique is useful at room temperature only.

Morrison and Kattus(7) of Southern Research Institute have developed an electrical system in which a number of fine wires are flash welded across the crack and the potential is measured when a 10 amp current is applied to the specimen.

The system is calibrated by comparison to standard specimens with known crack lengths. Unfortunately, this technique is usable only with brittle materials, since the system cannot discriminate between cracks and high elongation.

The use of surveyor's transits focused on a steel scale attached to the specimen have provided excellent results at Astronautics.

At -320°F, the specimen is immersed in liquid nitrogen contained in a cryostat with a viewing port and the same technique is used.

The computation of G_c is performed using a variation of the infinite plate formula that accounts for finite plate width as follows:

$$G_c = \frac{\sigma_G^2 W}{E} \tan \frac{\pi a}{W}$$

where W = specimen width in inches

Astronautics Test Program:

Specimens at Astronautics have consisted of rectangular center notch tensile coupons of two sizes: (1) 19" x 36" with a 5" center notch, (2) 4" x 10" with a 1¼" center notch.

Since the width to thickness ratio of the small specimen usually exceeds 45 (the maximum ratio recommended by ASTM) (8), doublers were spot welded to the ends of the specimen to provide both stiffness and more net area at the loading pins. Stability is provided for the large specimens by means of cast aluminum end fittings that are bolted to the specimen. Slots are cut in the specimens by the electrical discharge method (Elektrojet) with a .001 inch tip radius. (Fig. 1)

Observations of crack lengths by use of surveyor's transits have been verified by the Zyglo Penetrant technique.

A cryostat for testing the small coupons has been constructed and has been successfully used at both -320°F (liquid nitrogen) and -423°F (liquid hydrogen). (Fig. 2)

Testing has been performed in both Baldwin-Lima-Hamilton and Tinius-Olsen testing machines. In addition, the feasibility of using a dead load test machine was checked and found satisfactory.

TEST PROCEDURE:

Room Temperature:

(1) Install specimen in test machine

(2) Attach scale to specimen adjacent and parallel to the crack

(3) Focus surveyor's transits on scale and take no-load readings

(4) Apply load to specimen

(5) Take periodic readings on scale until failure of specimen

(6) Observe fracture appearance

Cryogenic Temperature:

(1) Install viewing cryostat in testing machine

(2) Install specimen with scale attached in cryostat

(3) Pull vacuum on casing of cryostat if needed

(4) Fill with liquified gas

(5) When cryostat is chilled, take zero reading with transits

(6) Apply load to specimen

(7) Take periodic readings on scale until failure of specimen

(8) Observe fracture appearance

Materials:

To date, while various materials have been tested, only 301 stainless steel has been evaluated sufficiently to obtain statistical accuracy.

The majority of tests performed have been on 301 extra full hard, but full hard, 3/4 hard and half hard have also been tested.

A limited number of transverse specimens and a few reworked samples of 301 were also tensile tested.

Sheet thicknesses ranged from 0.010" to 0.040".

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RESULTS:

To date, more than 50 crack propagations specimens have been tensile tested at room temperature and at -320°F. More recently, a considerable number of tests have been conducted at -423°F and the data will be contained in subsequent reports. A number of these have been used to develop test and instrumentation techniques. Others were designed to evaluate relative toughnesses of various materials with various tempers. It should be noted also that no conclusive testing has been done at Astronautics to evaluate the effect of thickness on fracture toughness although other experimenters (e.g. Berstein and Young) have concluded that there is a definite correlation.

Limited testing suggests that fracture toughness is influenced by degree of cold work, which is more or less in agreement with the notch-unnotch ratio indications. A series of 12 tests shows that the fracture toughness (and G_c) of 301 stainless steel sheet reaches a peak when the material is cold work to a hardness corresponding to a yield strength of approximately 160-170 ksi. Additional testing is required to verify these findings since control of chemical composition, etc. was not completely adequate.

A single heat and coil of 0.025" 301 SS (XFH) was used to evaluate the effect of temperature on K_c and G_c (see Table I). All specimens were of the same size and type except that half were from longitudinal and half were from transverse grain directions. It has been suggested (e.g. by Campbell) that a material should have a critical crack extension force (G_c) of at least 600 inch pounds per square inch to be considered usable for pressure vessels. If this criterian is used, 301 is suitable for use at 75°F and -320°F with average longitudinal values of 1642 and 1432 respectively. The toughness of the transverse sheet (747 at 75°F and 385 at -320°F) indicates a possible trouble area if the material is subjected to other than normal pressure vessel stress. The following should also be considered:

For a cylindrical pressure vessel,

$$\sigma_H \approx 2\sigma_L$$

where σ_H = hoop stress
σ_L = axial stress

Since $G_c = \dfrac{\sigma^2 W \tan \frac{\pi a}{W}}{E}$ and substituting,

$$G_c = \frac{(2\sigma_L)^2 \tan \frac{\pi a}{W}}{E} = \frac{4\sigma_L^2 \tan \frac{\pi a}{W}}{E}$$

Therefore if the G_c for the longitudinal sheet (hoop) is equal to 4 times the G_c for the transverse sheet (axial), the resistance to brittle fracture is equivalent in both directions.

If, however, the transverse G_c is less than four times the longitudinal G_c, the transverse then becomes the critical condition and should be the design criterion. Consider the test results obtained; at room temperature the transverse G_c is slightly less than half of the longitudinal G_c, which is acceptable. However, at -320°F, the average transverse G_c is only 27% of the average longitudinal G_c. The average values are acceptable, but just barely. If we use the extreme individual results within the groups, we find that the transverse value is 21% of the longitudinal value, or less than the 1-4 ratio.

If this trend continues with a decrease in temperature, it is likely that the 1-4 ratio will be greatly violated at -423°F and that the critical design criterion will be the transverse fracture toughness or the critical crack extension force (G_c). Further testing is underway to extend the fracture toughness data to the temperature of liquid hydrogen (-423°F).

In addition tests are underway to evaluate the toughness properties of fusion butt welds in high strength sheet alloys, including Types 301, 304 ELC 310, and 321 stainless steels, and the 5Al-2.5Sn titanium alloy over the temperature range of +75°F to -423°F. These tests are performed by making a transverse fusion butt weld across the 4" wide specimen and then slotting the specimen in the weld area. These tests are currently underway and the test results will be published shortly.

CONCLUSIONS:

1. The critical crack extension force (G_c) of 301 XFH, .025" longitudinal sheet is well above the arbitrary 600 figure recommended as a minimum at 75°F and -320°F. (5)

2. The G_c of transverse 301 XFH sheet may be marginal for use in pressure vessels at -320°F.

3. A small number of tests indicate that 301 stainless steel sheet has a maximum resistance to brittle fracture when the material has been cold-worked to give a yield strength of 160-170 ksi at room temperature.

RECOMMENDATIONS:

Design & Structures Groups

Re-evaluate design criteria for pressure vessels fabricated from 301 SS when used at -320°F or below to take into account possible brittle fracture in the transverse direction. Avoid requesting cold working of 301 SS to provide yield strengths above 190 ksi.

Research Groups

Actively pursue fracture toughness testing as follows:

(1) Determine G_c of all high strength materials being used and anticipated for use in advanced space vehicles over a temperature range including the proposed operating conditions.

(2) Determine effect of variation of thickness, amount of cold work, chemical composition, and temperature upon the fracture characteristics of high strength sheet materials used in critically stressed applications.

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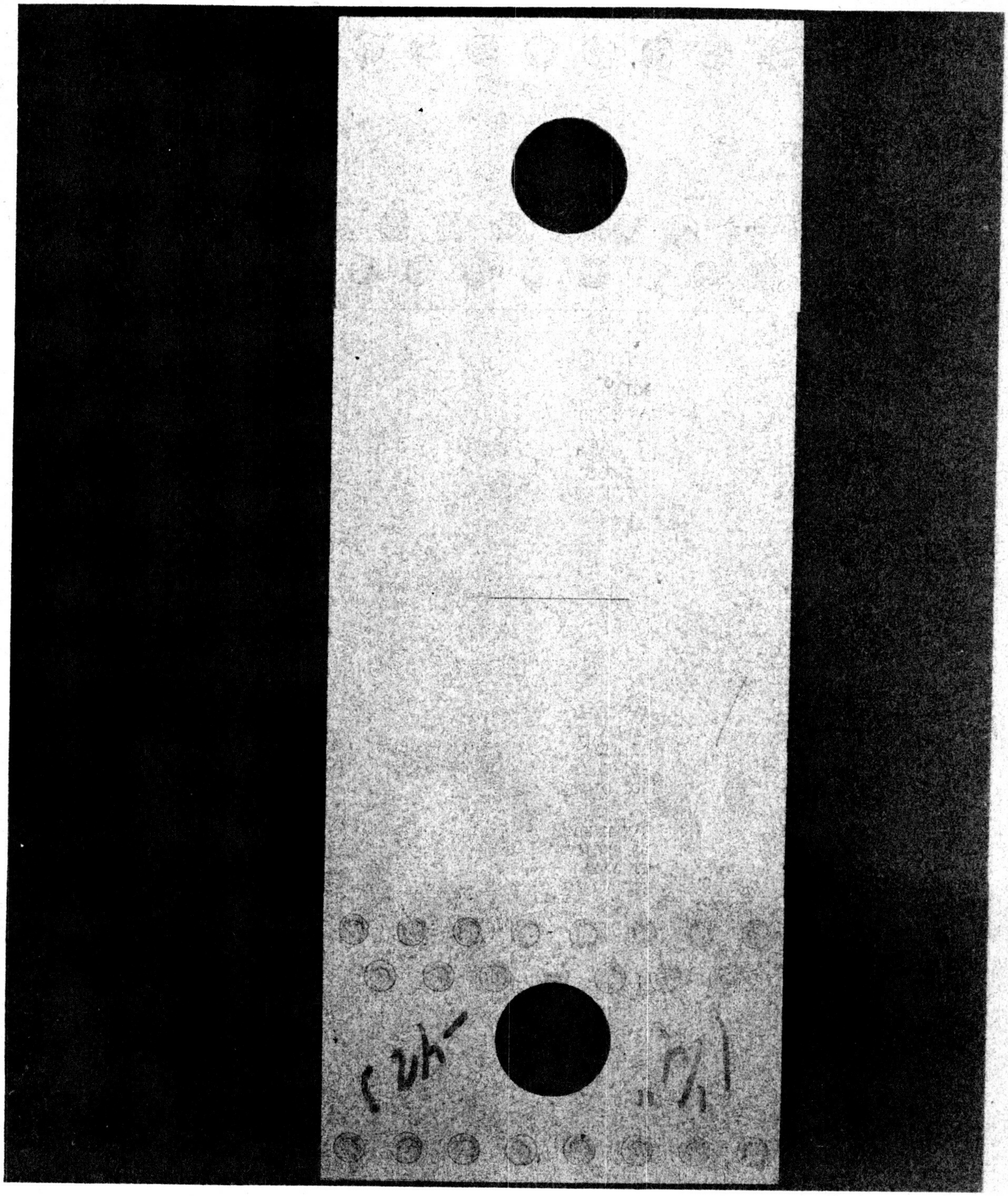

FIGURE 1 - Typical 4" x 10" Crack Propagation Specimen

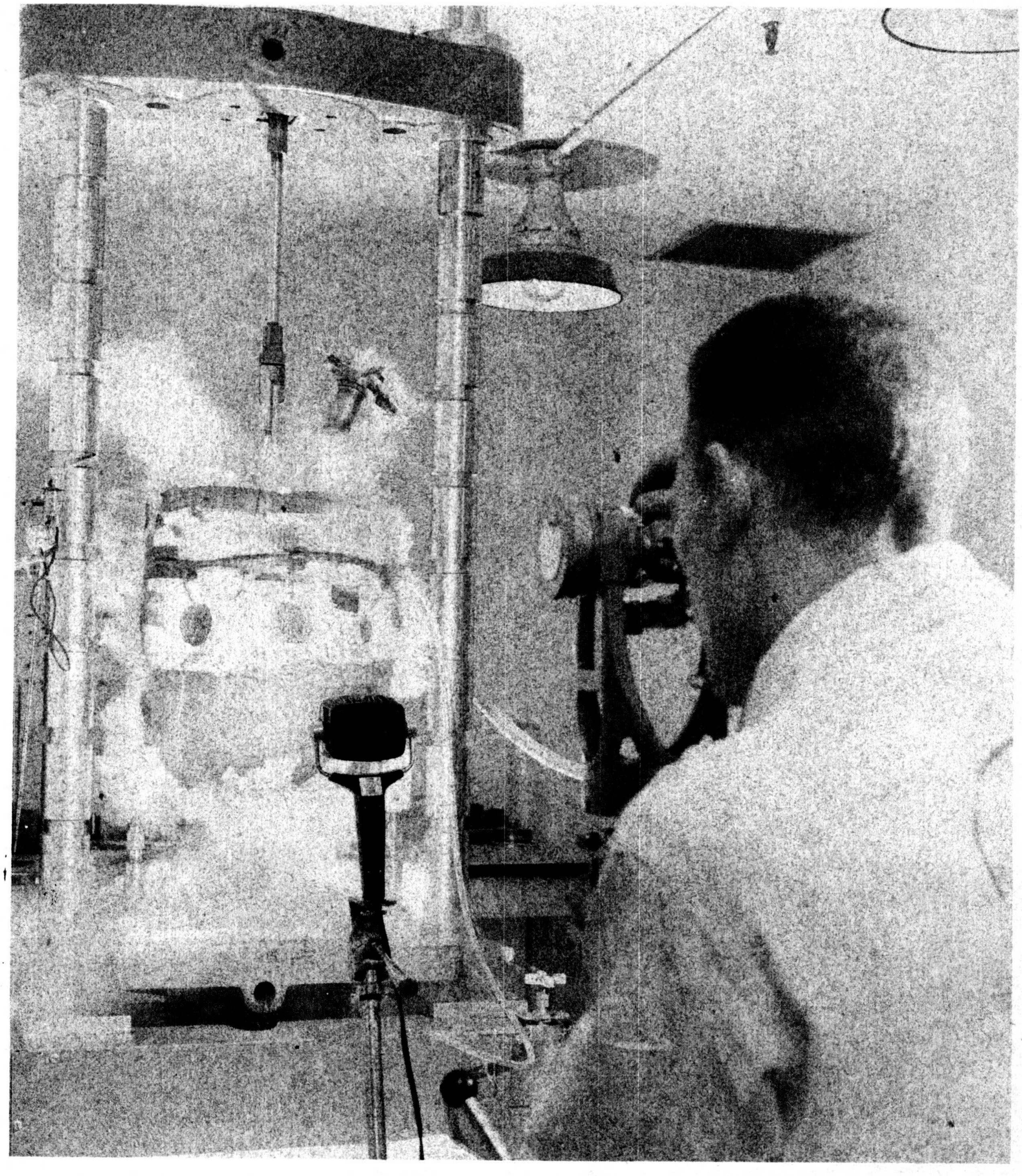

FIGURE 2 - Observation of Crack Propagating at -320°F

FRACTURE TOUGHNESS (K_c) & STRAIN ENERGY RELEASE RATE (G_c)

301 STAINLESS STEEL (XFH) Ht. 49061 Cl 7450 Ga 025

Spec. No.	F_{ty}	E/e	Notch Length	Test Temp	Critical Load"	Crit. Crack Len. (2a)	Gross Stress	Net Stress	Fract. Toughness (Kc)	G_c	
L-1	200	25.3/10.8	1.24	78	10200	1.90	105	200	202	1615	
L-2			1.26	78	10200	1.90	103	195	198	1550	
L-3			1.25	78	10600	1.92	107	206	207	1695	
L-4			1.25	78	10700	1.89	108.5	206	208	1710	
Average									204	1642	
L-6	254	30.1/19.8	1.24	-320	10650	1.82	108.2	198.5	202	1355	
L-7			1.23	-320	10800	1.95	109.5	214	219	1595	
L-8			1.23	-320	10900	1.90	111	212	214	1520	
L-9			1.24	-320	10700	1.60	109	182	186*	1150	*Spec.delaminated
L-10			1.24	-320	10500	2.00	107.5	215	215	1540	
Average									206	1432	
T-1	176	27.2/7.5	1.26	78	7400	1.90	75	142	144	763	
T-2			1.26	78	7400	1.84	74.5	138	140	720	
T-3			1.25	78	7600	1.88	76.5	144	146	785	
T-4			1.23	78	7800	1.72	78	137	140	720	
Average									142	747	
T-5	235	31.2/16.1	1.23	-320	7700	1.23	78	112.5	113	410	
T-6			1.25	-320	7000	1.4	70.5	110.5	110.5	392	Crit.Crack Length Unverified
T-8			1.24	-320	6600	1.34	67.3	101	103	340	
T-9			1.24	-320	6600	1.47	66.9	105.7	108	374	
T-10			1.24	-320	6900	1.47	70.2	111	113	410	
Average									109	385	

TABLE 1.